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Contribution of fuel cell systems to CO_2 emission reduction in their application fields

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ABSTRACT

Fuel cells (FCs) and their hybrid systems can play a key role in reducing carbon dioxide (CO_2) emissions. The present paper analyzes the contributions of the FC system to CO_2 emission reduction in three application fields.

In the mobile application field, the direct methanol FC system has little or no influence on CO_2 emission reduction.

The benefit of the FC in CO_2 emission reduction in the transportation field is directly dependant on the H_2 production method. Pre-combustion technology (with carbon capture) represents one of the best mid-term solutions for H_2 production. If FC vehicles (FCVs) use the H_2 produced by this process, the CO_2 emissions in this field could be decreased to 70–80% of the traditional CO_2 emissions.

In the stationary application field, the FC system can be effectively operated as the distributed generation (DG) in terms of CO_2 emission reduction. Among the various types of FC or FC hybrid system used for DG, the solid oxide FC (SOFC) hybrid system with a CO_2 capture unit is the best option as it doubled the electricity efficiency compared to the traditional combustion cycle and decreases the CO_2 emission to 13.4% of the traditional CO_2 emission.

However, the FC and carbon capture and sequestration (CCS) technologies need to be fully developed before the FC can contribute to reducing CO_2 emissions.

Contents

1. Introduction

The effect of greenhouse-gas (GHG) emissions on climate change is currently believed to be one of the most dangerous problems threatening human life. According to the fourth report by IPCC [1], the global surface temperature and sea level have

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increased by 0.3–0.6 °C and 10–25 cm over the last century, respectively. Furthermore, if any other supplementary actions for GHG reduction are not taken in the near future, 40% of the species worldwide may be threatened with extinction. The reduction of GHG emissions has therefore attracted extensive research efforts worldwide.

Generally, CO_2 emissions from energy use could be reduced by three options. The first is the improving the conversion efficiency of energy devices such as boiler, turbine, engine, furnace, and motor. The second way is the use of renewable and sustainable energy such as solar, wind and hydrogen (H_2) energies which emit little GHGs. Final option is the development of the energy production or conversion system essentially applicable to carbon capture and storage (or sequestration) (CCS) technologies. Each option can substantially reduce CO_2 emissions. The system combining two or three of these options can greatly decrease the CO_2 emissions due to their synergy effect.

Therefore, fuel cells (FCs) and their hybrid system represent one of the most promising technologies to effectively reduce CO_2 emissions as they simultaneously satisfy the three conditions, as shown in Fig. 1, by using clean energy from H_2 with a high theoretically conversion efficiency of about 83% [2–4] and a system configuration that facilitates the easy capture of CO_2.

The use of the FC system will therefore directly or indirectly reduce CO_2 emissions. For example, when the FC vehicle (FCV) use the H_2 produced by the reforming process integrated with CCS technology, FCV use will greatly reduce CO_2 emissions. The molten carbonate FC (MCFC) system can generate electricity with high efficiency while concentrating or separating the CO_2 from the conventional combustion gas mixture [5]. Furthermore, hybrid power stations such as solid oxide FC (SOFC), micro gas turbine (μ-GT) can substantially improve the electrical efficiency while operating effectively and systematically for CO_2 capture.

Consequently, FC systems will substantially reduce CO_2 emissions. In fact, POSCO Power, which is one of the subsidiary companies of POSCO and a coordinate company with Fuel Cell Energy (FCE), has obtained approval from the UN for a new fuel cell (MCFCs) clean development mechanism (CDM) methodology in July 2009 [6]. This is the world's first case that officially proved the contribution of the FCs to CO_2 emission reduction. In addition, this is evidence that technologically supports the benefits of the FCs in terms of CO_2 mitigation. Based on this decision, the company is known to have prepared for registering the CDM credits and requesting the emission rights.

Many papers [7–18] have reported the FC contribution to CO_2 emission reduction in the last decade. Although they presented very constructive information, they have not been strongly emphasized in terms of CO_2 emission reduction and CCS.

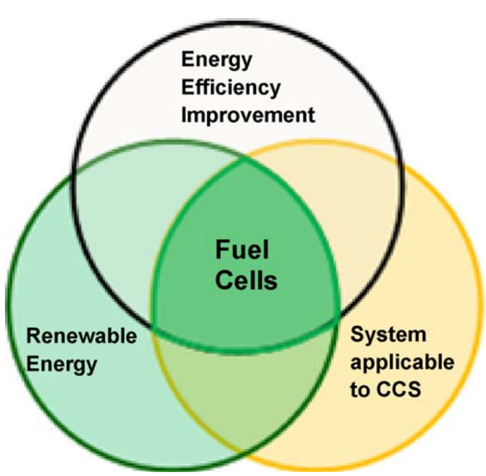


Fig. 1. Options for CO_2 emission reduction in energy use and the roles of fuel cells.

Under the current state of initiation of the FC's commercialization and of focusing on climate change, an integrated review analysis needs to be conducted on the benefits of FC systems in CO_2 emission reduction. However, this investigation is not simple because many factors, conditions, and assumptions must be appropriately considered. These include the carbon footprint determination of the every element in the FC application fields, a full technological chain of FCs and their medium/long term scenarios, and government initiatives of the FCs and CO_2 emission reductions. If these all are considered, the paper might become a book.

Therefore, the present review paper simply analyzes and discusses the roles and contributions of FC systems to CO_2 emission reduction focusing solely on technologically important factors such as energy use and energy efficiency.

Firstly, in this paper, the FC application fields are divided into three sectors where the FC system is most widely used: mobile (portable), transportation and stationary fields. Secondly, the CO_2 avoidance in each sector, which is directly regarded as the amount of CO_2 emission reduction gained by using the FC or its hybrid system, is estimated based on some assumptions and on some previously published results.

2. Mobile application field

The market for portable and micro-electronic devices such as laptop computers, cellular phones, and personal digital assistants (PDAs) has greatly increased. These devices require greater density and longer operation time to satisfy the requirements for mobile services. The direct methanol FC (DMFC) is considered one of the most promising candidates to complement or substitute for the traditional power supply in the mobile application field and represents the future technology for portable power supplies. However, DMFC system releases some CO_2 gas during operation, the amount of which has been estimated in a previous review paper [19]. In this work, I reported an annual theoretical CO_2 gas emission of about 16.7 kl (or 32.8 kg at standard state) for a 20W, DMFC-powered laptop operated for 8 h a day. Furthermore, the paper also presented the methanol consumption and electricity savings at the same operating condition.

With these results and some additional data, the contribution of the FC system, especially DMFC, to the mitigation of CO_2 emissions in mobile application fields could be roughly estimated. The same assumptions of the previous paper [19] were also applied and the number of laptop computers in the country was considered. In Korea, about 5.6 million laptop computers were sold in the 4-year period of 2005–2008 and if they all use DMFC for the power supply, the total electric energy for operating these laptops was calculated to be 336,000 MWh, the generation of which would require 165,000 tonnes of methanol and would emit 183,680 tonnes of CO_2 per year, excluding any CO_2 emission from the methanol and DMFC production. This compares to an average CO_2 emit coefficient of 573 CO_2 g kW^{-1} h^{-1} for electricity use in U.S. according to the data from IEA (2005). Ignoring other energy losses, the total CO_2 emission to generate 336,000 MWh of electricity can be calculated as about 192,528 tonnes. This CO_2 emission can be balanced by the use of DMFC as a power supply, instead of batteries charged from the power grid, for the 5.6 million 20 W-laptops previously calculated. This CO_2 avoidance value is similar to the annual CO_2 emission of 183,680 tonnes from the DMFC system. Therefore, this can be compensated by the CO_2 avoidance value obtained from the power plant. Considering the carbon footprint of the methanol and the DMFC system, the contribution of the FCs in this field might be slightly negative. However, the absolute amount of these two

values is more important to address the FC contribution in the mobile application field. They are completely negligible (about 0.03%) compared to the total national annual GHG emission amount (gross based) of about 600 million tonnes of CO_2 equivalent [20]. Even if the application of DMFC was expanded to other mobile devices such as cellular phones and PDAs, their relatively small power output compared to laptops would negate the significance of any emission savings. Therefore, the application of FCs in the mobile field has little or no influence on CO_2 emission reduction. Therefore, the FCs with even higher efficiency for mobile application should be studied further via the system development and use of cleaner fuels.

3. Transportation application field

In 2006, the CO_2 emissions from the transportation sector in Korea were estimated to be 100 million tonnes. This is about 20% of the net amount of total nation's CO_2 emission per year. The transportation emissions primarily result from the 17 million automobiles in the country. It is very easy to estimate the contribution of FC to CO_2 mitigation in this field. For example, if a quarter of the automobiles in the country were substituted by FCVs using H_2 produced by the carbon-free process, about 25 million tonnes of CO_2 emission can be avoided annually. As stated earlier, this field has the greatest potential for practical reductions in CO_2 emissions.

However, the H_2 production and use should be addressed prior to a description of the FC effects in this field in terms of CO_2 mitigation because the benefit of FC application in this field is directly dependant on these issues. The CO_2 emitted from the traditional inner combustion engine (ICE) car cannot be easily captured or directly reduced. Therefore, the only way to reduce the CO_2 emissions in this field is by using H_2 as the fuel. In addition, the H_2 can act as an efficient and clean energy carrier and storage medium. The H_2 production therefore remains the key.

The worldwide H_2 market is currently estimated to be over about $282 billion per year and is growing at 10% annually. Moreover, it will rise between 20 and 40% per year by next 10 years and is anticipated to reach several trillion US$ by 2020 [16]. However, most of H_2 is currently produced by catalytic steam reforming using hydrocarbons, which releases a great amount of CO_2 into atmosphere. If the FCs in the transportation field use the H_2 produced from this reaction, then they will not contribute to CO_2 emission reduction. In fact, considering the additional energy required for reforming, FCV could exert more negative impacts than traditional ICE vehicles. Therefore, to avoid CO_2 emissions in this field, the H_2 has to be generated from the carbon emission-free sources such as from water electrolysis with nuclear, wind, and solar energy. If such H_2 was used as fuel for FCVs, the contribution of the FC system in this field would be enormous.

The report [16] by Haseli et al. investigated this matter by examining the comparative CO_2 emissions from the four types of passenger train powered by conventional ICE, electrified, hydrogen ICE, and proton exchange membrane FC (PEMFC) traveling between Oshawa and Toronto, Canada. For the electrified train, CO_2 emitted from the electricity generation by natural gas (NG) and coal-burning power plants was taken into consideration. They also assumed some additional conditions such as several H_2 production methods. With these conditions, they compared the CO_2 emissions of each train system.

They claimed that the train powered by PEMFC fueled by H_2 produced by combined wind energy and a thermo-chemical copper-chlorine plant is the most environmentally friendly case, as shown in Fig. 2.

They estimated the CO_2 emissions from this case as 1.207 kg km^{-1} of travel distance, which is only about 9% of a conventional diesel train or electrified train at 13.32 kg of CO_2 km^{-1} of travel distance.

As mentioned, the FC contribution to CO_2 emission reduction in the transportation field is strongly dependent on the H_2 production process and cost. However, its cost by solar cell and wind turbine is known to be about 3.63 and 3.1 US$/kg of H_2, respectively [21]. These values are even higher than the commercially available H_2 cost of 1.5–2 US$ kg^{-1}, which is slightly lower than that of H_2 produced by the traditional reforming using NG without CO_2 capture.

In addition, solar cells, wind turbines and other clean energy sources can be used in small scale and restricted environment. Therefore, the process combining conventional H_2 production using NG with CCS technology has been termed "pre-combustion technology" in terms of environment and is considered the most feasible mid-term option [22]. This process is performed with widely used H_2 production processes such as steam reforming, partial oxidation, and auto-thermal reaction, as well as CCS technologies such as chemical, physical absorption, adsorption,

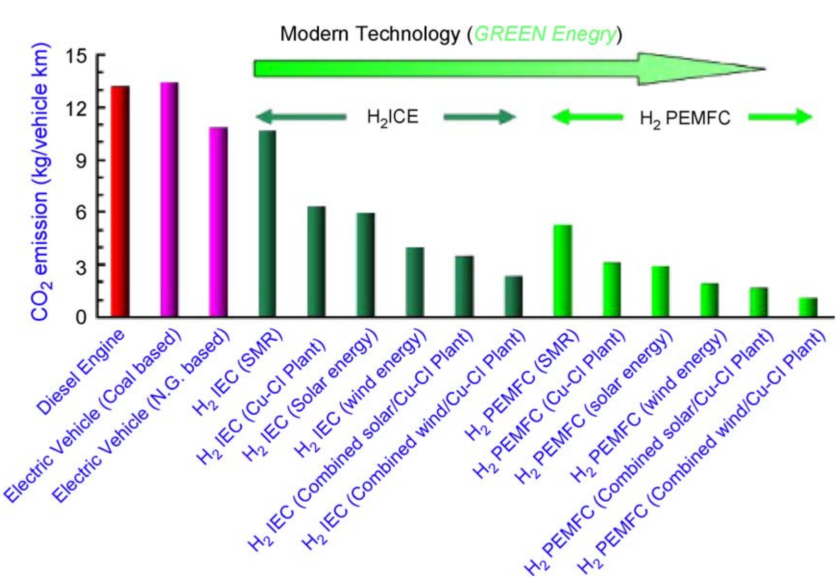


Fig. 2. Greenhouse gas emissions from different trains with various fuel production methods [16].

condensation, chemical looping and membrane processes [23,24]. The pre-combustion technology can also include the more advanced and future power generation technologies using coal such as the pulverized coal (PC), integrated gasification combined cycle (IGCC), and zero emission coal (ZEC) concepts [15].

H_2 storage, delivery, utilization and social environment are other essential factors to investigate the FC contribution in the transportation field. This issue is not entirely applicable to FCs, Many papers [25–32] have continuously reported the potential H_2 economy and environmental effect with positive or negative views. The FC contribution in the transportation field cannot easily be analyzed if all these factors are considered. However, this issue can be narrowed to some extent. In solar powered H_2 production and refueling station for vehicles in Sacramento [33], which is one of about 60, small scale, H_2 refueling stations currently operated as test projects [34], the additional energy consumption is only for compression of H_2 for storage and refueling because H_2 production and refueling are carried out on-site.

As the major focus of this paper is not to report on the carbon-free H_2 production or other factors, the present description is concluded with a recently presented paper [35] claiming that the FCV using H_2 produced from pre-combustion technology and considering a well-to-wheels comparison of CO_2 emissions can significantly reduce CO_2 emissions in the transportation field.

In this paper, Dougherty et al. [35] reported the CO_2 reduction benefits using H_2 as a transportation fuel in the US environment. According to the paper, except for biomass as a H_2 source, centralized NG and coal-based reforming with CCS are the most effective H_2 production options in terms of CO_2 emission reduction, as shown as the fourth and sixth bars in Fig. 3.

In addition, they also compared the well-to-wheels CO_2 emissions at the conditions shown in Fig. 4.

According to their paper, the FCV system using H_2 produced by the centralized NG and coal reforming with CCS technology was calculated to give CO_2 emissions of 150 and 230 g per mile of travel distance, which are less than 20 and 30%, respectively, of the value for conventional gasoline ICE of 780 g of CO_2 per mile.

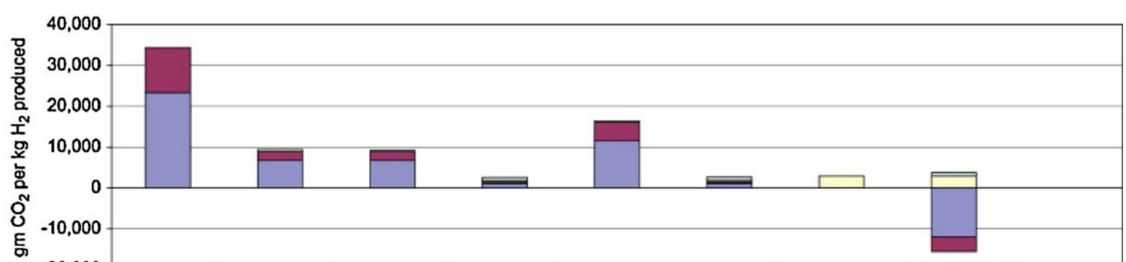
The results presented in these two papers suggest that if some challenges in H_2 production and the CCS technologies can be overcome, the FC system can significantly reduce CO_2 emissions by up to 70–80% of the traditional ICE emissions.

4. Stationary application field

The FC contribution in this field is not as directly related to the H_2 production as is the transportation application field because the high temperature FCs such as MCFC and SOFC that are used in this field can use the H_2 produced directly by on-site conventional NG reforming. Therefore, if the CO_2 capture technology of the post-combustion method were effectively applied to this field, the CO_2 emissions could be reduced more easily than in any other application field.

In this field, the FC can be operated most effectively with distributed generation (DG). DG is generally accepted as being applicable to small scale power generation technologies or combined heat and power (CHP) generating units at or near the customer sites with a power capacity of 50–100 MW [36,37].

Therefore, DG can be effectively used in breweries, industrial and municipal waste water treatment facilities, hotels, universities, manufacturing, mission critical/data communication centers, government, grid support, hospitals/clinics and prisons [37]. DG suffers from very high operating costs. Nevertheless, the market for DG is growing due to its advantages of high energy efficiency and low pollution.



	on-site electrolysis	on-site NG reforming	Central NG reforming (no sequestration)	Central NG reforming (with sequestration)	Central coal reforming (no sequestration)	Central coal reforming (with sequestration)	Central biomass reforming (no sequestration)	Central biomass reforming (with sequestration)	Central electrolysis (from wind)
Sequestration	0	0	0	816	0	816	0	816	0
Process fuels	0	536	399	399	399	399	2,930	2,930	0
Feedstock losses	10,994	2,126	2,073	311	4,491	404	0	-3,576	0
Feedstock	23,337	6,756	6,756	1,013	11,545	1,0390	0	-11,973	0

Fig. 3. CO_2 emissions per kg H_2 for various production options [35].

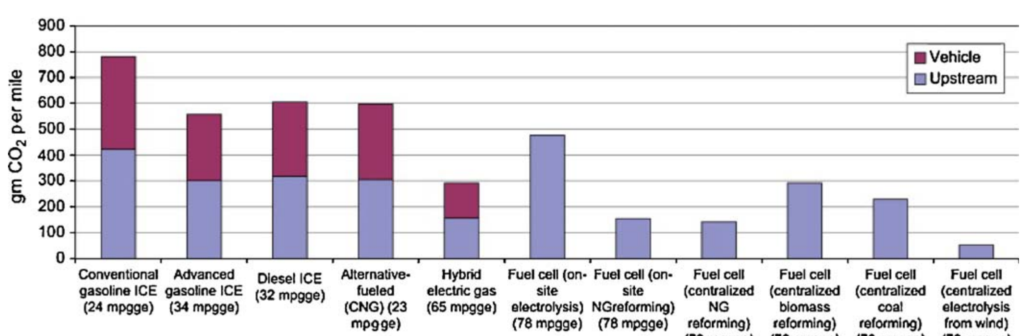


Fig. 4. Well-to-wheels comparison of CO_2 emissions per mile for cars [35].

All renewable and sustainable energy systems such as solar cells, wind turbines and FC systems can be operated as DG systems. However, this paper only examines DG systems for the stand-alone FC or its hybrid system based on NG (or coal) as the fuel. NG demand is rapidly growing and will become an increasingly important fuel in the future due to its relatively lower CO_2 emission, ease of production and inherent safety. Therefore, many countries in the world are trying to increase this system and its share will be very important in the future [36,38].

Among FC-based DG systems, the MCFC and SOFC hybrid systems, which is an integration of FC with GT or steam turbine (ST) is considered to be the most attractive system for two reasons. One is its higher electricity efficiency than that of the traditional (integrated) combined cycle [24,39,40]. The average electrical efficiency of the traditional combined cycle is known to be in the range of 30–35%, based on LHV (However, the latest coal-based power plants, called ultra-super-critical, may achieve 38%.). Despite the higher theoretical efficiency of several advanced cycles such as PC, advanced ultra-super-critical (A-USC), IGCC and NG combined cycle (NGCC), which are all at the stage of demonstration or R&D, their practical efficiencies cannot be far beyond 40% [11].

However, the FC system has greater potential to improve the electric efficiency by using the FC–GT or ST hybrid system. There are three types of FC hybrid power generation [8]: the FC–ST hybrid system, which is the simplest way for FC integration with steam cycles [41], the FC–GT, and the FC–GT–ST hybrids. It is known that the NG-based SOFC–GT hybrid systems can be practically operated at an electrical efficiency reaching the range of 45–50% [41,42]. However, the overall electrical efficiency of this system can theoretically approach 60–65% [41], and can be further improved by adding an ST cycle to drive the overall electrical efficiency into the mid-seventies [11,40,43].

The MCFC and SOFC hybrid systems have also attracted attention as future energy sources for DG due to their ability to provide new and effective options of CO_2 capture. Basically, MCFC and SOFC are operated by separating the air flow in cathode from the fuel flow and its products in the anode. Most of the products from the anode are CO_2 and water. The small amounts of unreacted fuel and CO that are also presented in the anode exhaust can be used as an additional fuel for GT. Therefore, these system features can prevent the complete mixture of the fuel and air flow, and also offer an effective option for CO_2 capture [7,8,44].

Earlier studies on CO_2 capture of FC hybrid system were published by van Schie and Goettlicher [13], followed by many investigations on the system's performance. Nevertheless, as this system remains at the conceptual level, it is very difficult to demonstrate and the most of reported results were based on modeling because the two dependent technologies included in this system, i.e., FG hybrid and CCS, have not yet been sufficiently developed for effective adoption. CCS technology may take 20 years before becoming practically and economically viable. However, the various FC hybrid systems, either with or without a CO_2 capture unit, have been extensively studied and many studies published due to their highly advantageous features. These efforts are summarized in the next section according to the system types.

4.1. MCFC system

The MCFC system is closer to commercialization than the SOFC system. For example, FCE-POSCO Power presented a plan to release their 2.8-MW product by 2009 [37,45]. In MCFC, an air mixture containing CO_2 gas at the composition of approximately 30 mol% is supplied to the cathode for supplement of CO_3^{-2} as ion transfer and it is reproduced at the anode with a higher concentration. Therefore, the MCFC system is more systematically advantageous for CO_2 capture than the SOFC system. The MCFC hybrid system includes MCFC–GT and MCFC–GT–ST, as well as these systems with a CO_2 capture unit.

4.1.1. MCFC hybrid system

The contribution of this system to CO_2 emission reduction can be evaluated by its higher electric efficiency compared to the stand-alone MCFC and traditional combustion systems.

In 2006, Williams et al. reported the experimental results on this system which included a 250 kW MCFC-30 kW modified μ-GT. The system was successfully operated over a life-span of 6800 h with an electric efficiency of 52%. They claimed that this efficiency was even higher than that of their stand-alone MCFC system of 45–48% [37]. The performance of this NG-based system, as presented by the other studies [46–49] is summarized in Table 1 and its electricity efficiency was in a range from 52 to 70% which is about twice the efficiency of a traditional NG-based combustion power plant.

4.1.2. MCFC hybrid system with a CO_2 capture unit

The CO_2 emission could be more systematically and directly reduced by using a CO_2 capture unit for the exhaust streams of the MCFC hybrid system.

An impressive work [7] on this system was presented in 2002 by Campanari et al., who investigated the CO_2 removal efficiency of the MCFC–ST hybrid system via the modeling. In this work, NG-based MCFCs were applied to the super-critical coal steam plants as a sub-power generator and a CO_2 extractor. In this system, the steam cycle exhaust and added air were used as the cathode gas of the MCFC, as shown in Fig. 5.

In addition, they used a physical absorption unit to capture the CO_2 emitted from the process. Together with some additional assumptions, they claimed the electrical efficiency of steam plant could be maintained at about 45%, while additional electricity could be obtained from the MCFC system with an efficiency of 40%. Furthermore, they also claimed that their system could separate 76.9% of the CO_2 otherwise vented.

Table 1
Various MCFC hybrid systems and their efficiencies reported from the literature.

FC hybrid systems	Fuel	Net electric efficiency (%)	Remarks	Reference (published year)
MCFC (250 kW)–μ-GT[a] (30, 60 kW)	NG	52 (45–48% for stand-alone MCFC)	Successfully operated during the life-span of 6800 h	[37] (2006)
MCFC (20 MW)–GT–ST[b]	NG	69.5 (58% for stand-alone MCFC)	Tri-generation, at atmosphere	[46] (2004)
MCFC–GT[b]	NG	59.2		[47] (2002)
MCFC–GT[b]	NG	59.7	Integrated GT compressor	[48] (2003)
MCFC–GT–ST[b] (10–15 MW)	NG	69.1	1- and 2-level HRSG (Heat Recovery Steam Generator)	[49] (2002)

[a] Field-demonstration.
[b] Modeling.

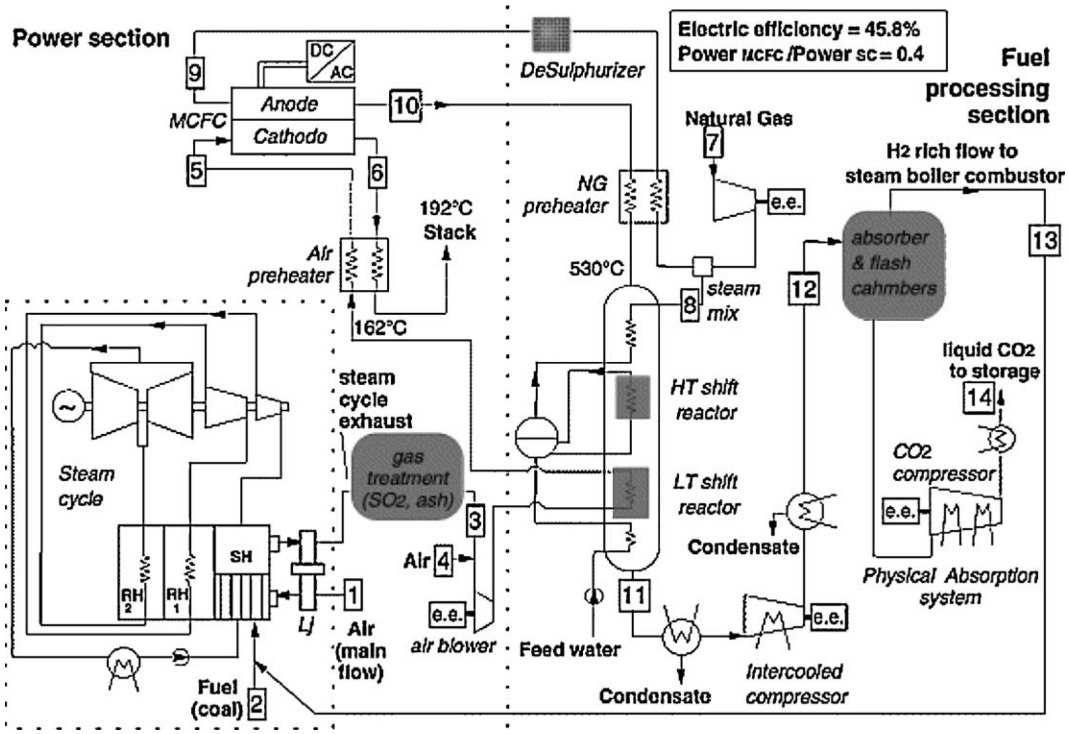


Fig. 5. CO_2 separation from a conventional power plant by integration with a MCFC plant [7].

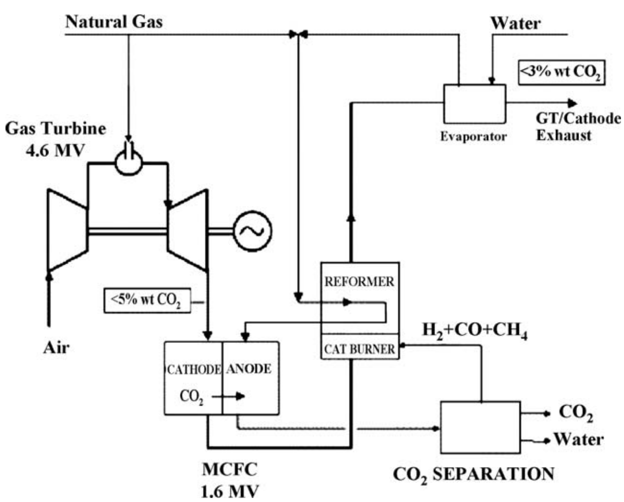


Fig. 6. Hybrid atmospheric pressure MCFC scheme for CO_2 capture [5].

In 2004, Amorelli et al. [5] reported the performance of the MCFC hybrid system with CO_2 capture which included a 4.6 MW GT, 1.6 MW MCFC and condenser for CO_2 capture. The system was NG-based and its configuration is shown in Fig. 6.

In the system, the exhaust gas from the GT operation, which is a mixture of 5% CO_2 and air, was fed to the MCFC cathode. The system was claimed to reduce the CO_2 emissions by 50% compared to the solely GT system. However, authors did not report the electric efficiency and they raised issues on the contaminants for the FCs by SO_x and NO_x from the exhaust gas.

The other studies [50] on this system are summarized in Table 2. NG-based electric efficiencies are on average 10% lower than that of the system without a CO_2 capture unit.

Instead, CO_2 capture with a reduction efficiency range of 58–91% can be additionally obtained in this system. Therefore, the favorability of the CO_2 capture unit in terms of net CO_2 emission needs further study. Nevertheless, the efficiency of the MCFC hybrid system with a CO_2 capture unit is still higher than that of the traditional burning cycle.

Table 2
Various MCFC hybrid systems with CO_2 capture units and their performance by modeling reported from the literature.

FC hybrid systems	Fuel	Net electric efficiency (%)	CO_2 capture (or reduction) efficiency (%)	CO_2 capture technology	Remarks	Reference (year)
MCFC (197.6 MW)–ST (450 MW)	NG (MCFC) ST (Coal)	45.8	76.9	Physical absorption	Apply to super-critical coal steam plants	[7] (2002)
GT (4.6 MW)–MCFC (1.6 MW)	NG	–	50 (Relative to stand-alone GT)	Condensation	Contamination of NO_x, and So_x from GT exhaust gases	[5] (2004)
MCFC–ST	Coal	35[a]	68	Physical absorption	IGCC including WGS process	[50] (1998)
MCFC–ST	Coal	36[a]	76	Chemical absorption	IGCC process	[50]
MCFC–ST	NG	49[a]	58	Physical absorption	NGCC including WGS process	[50]
MCFC–ST	NG	55[a]	91	Chemical absorption	NGCC process	[50]

[a] Including CO_2 compression to 110 bar.

Table 3
Various SOFC hybrid systems and their efficiencies reported from the literature.

FC hybrid systems	Fuel	Net electric efficiency (%)	Remarks	Reference (year)
SOFC (176 kW)–μ-GT[a] (47 kW)	NG	57 (net AC/LHV)	Electrical efficiency of SOFC-CHP system is 46% 3.5 atm pressurized SOFC Testing by ETS (Edison Technology Solutions)	[11,51] (2000)
SOFC–GT[a]	NG	65	GE is collaborating with NETL	[37] (2006)
SOFC–GT[b] (∼MW)	Coal	60	GT and double SOFCs system	[53] (2006)
SOFC–GT–ST[b] (10 MW)	NG	65.3	HRSG integrated	[54] (2008)
SOFC (20 MW)–GT–ST[b]	NG	67.5 (56% for stand-alone SOFC)	Tri-generation, at atmosphere	[46] (2004)
SOFC (23.6 kW)–μ-GT[b] (6.4 kW)	NG	66.5	Integrated GT compressor	[44] (2004)
SOFC-μ–GT[b] (250 kW)		64.9		[55] (2000)

[a] Field-demonstration.
[b] Modeling.

4.2. SOFC hybrid system

Currently, the SOFC hybrid system is considered more competitive than the MCFC hybrid system in the DG application field due to its higher temperature and higher efficiency. Therefore, more reports on this system have been published than on the MCFC system, as listed in Tables 3 and 4. These are presented in the following section.

4.2.1. SOFC hybrid system without CO_2 capture

Following the successful demonstration of the world's first SOFC–GT hybrid system by Siemens-Westinghouse in 2000, California [51], this system has attracted a great deal of research effort. The demonstration system consisted of five major subsystems: 176 kW-SOFC module, fuel supply, thermal management including the 47 kW-μ-GT generator, electricals, and power dissipation devices, as shown in Fig. 7.

In the process, the exhaust gas mixture from SOFC and the desulfurized NG gas are combusted for expansion in the μ-GT for power generation. An electrical efficiency of 57% was claimed for this system.

GE is collaborating with NETL (National Energy Technology Laboratory) to develop this system using the commercial GT for DG power applications. According to one paper [37], a preliminary design for high temperature heat exchangers for this system has been developed, and pressurized operation of planar SOFC stacks has

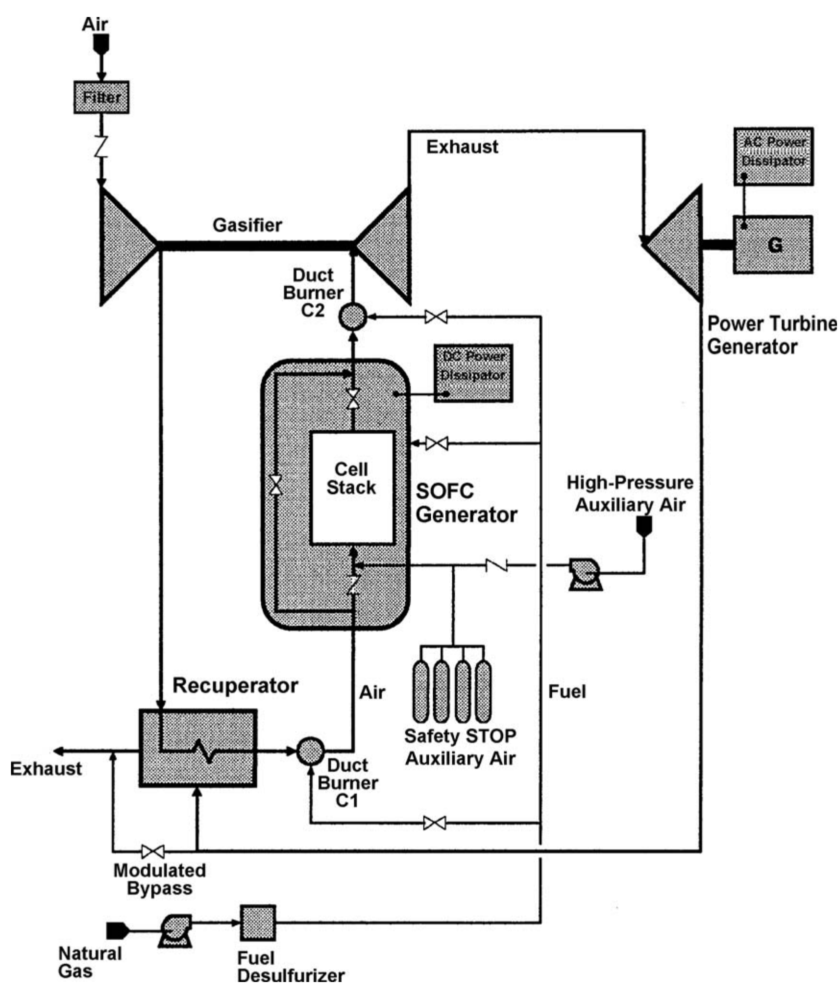


Fig. 7. 220 kW SOFC–GT power system flow schematic [51].

Table 4
Various SOFC hybrid systems with CO_2 capture units and their performance by modeling reported from the literature.

FC hybrid systems	Fuel	Net electric efficiency (%)	CO_2 reduction (or capture) efficiency (%)	CO_2 capture technology	Remarks	Reference (year)
SOFC–GT	NG	64.3		None		[36] (2004)
SOFC–GT (50–100 MW)		63	67	Amine absorption	CCS	
SOFC–GT (400 MW)	NG	67.3	99	Condensation and compression	400 MW is too large for FCs	[56] (2006)
SOFC–GT (1.5 MW)	NG	61.7	–	None		[14] (2008)
SOFC–GT –CCS		44.7	70.5	Amine absorption	CCS	
				Steam condensation		
SOFC–GT–CCS		58.2	100		CCS	
SOFC–GT	Coal	73	96	Chemical looping	ZEC concept	[57] (2008)
SOFC–GT	Coal	45–50	90	Various strategies	IGCC	[58] (1999), [59] (2002)
SOFC–GT	Coal	71	100	Pre-combustion (Chemical adsorption)	IGCC and ZEC	[60] (2001)
SOFC–GT	NG	46–69	90	Chemical absorption		[24]
SOFC–GT	NG	59–67	80–100	After burner		[24]

been demonstrated. With these technologies, the working group claimed that their proposed hybrid system could achieve an electricity efficiency of 65%.

A study on this system focused especially on the FutureGen which is an international program for the development of various clean energy technologies for coal [52] (However the progress of the FutureGen program is known to substantially be delayed.). In the program, some researchers predicted this system efficiency could reach 60% with near zero emission [53].

In 2008, Arsalis [54] reported the thermo-economic modeling performance of a 10 MW SOFC–GT–ST hybrid system with an average electrical efficiency of 65.3%.

Other performance reports [46,55] are listed in Table 3 despite some variation in the configuration of the SOFC hybrid systems, the electricity efficiency was estimated to be 57–70%, which is slightly higher than that of the MCFC hybrid system.

4.2.2. SOFC hybrid system with a CO_2 capture unit

A SOFC hybrid system equipped with a CO_2 capture unit appears to be the most desirable technology for FC-based DG application in the near future. The many recent papers supporting this fact are listed in Table 4.

In 2004, Möller et al. [36] compared the performance of an SOFC–GT system with that of one with the CO_2 capture of amine absorption. Their system configuration is shown in Fig. 8.

In their modeling, the electric efficiency of both systems was similar at about 64% and the CO_2 removal efficiency of the SOFC–GT with a CO_2 capture unit was estimated to be 67%. Based on these

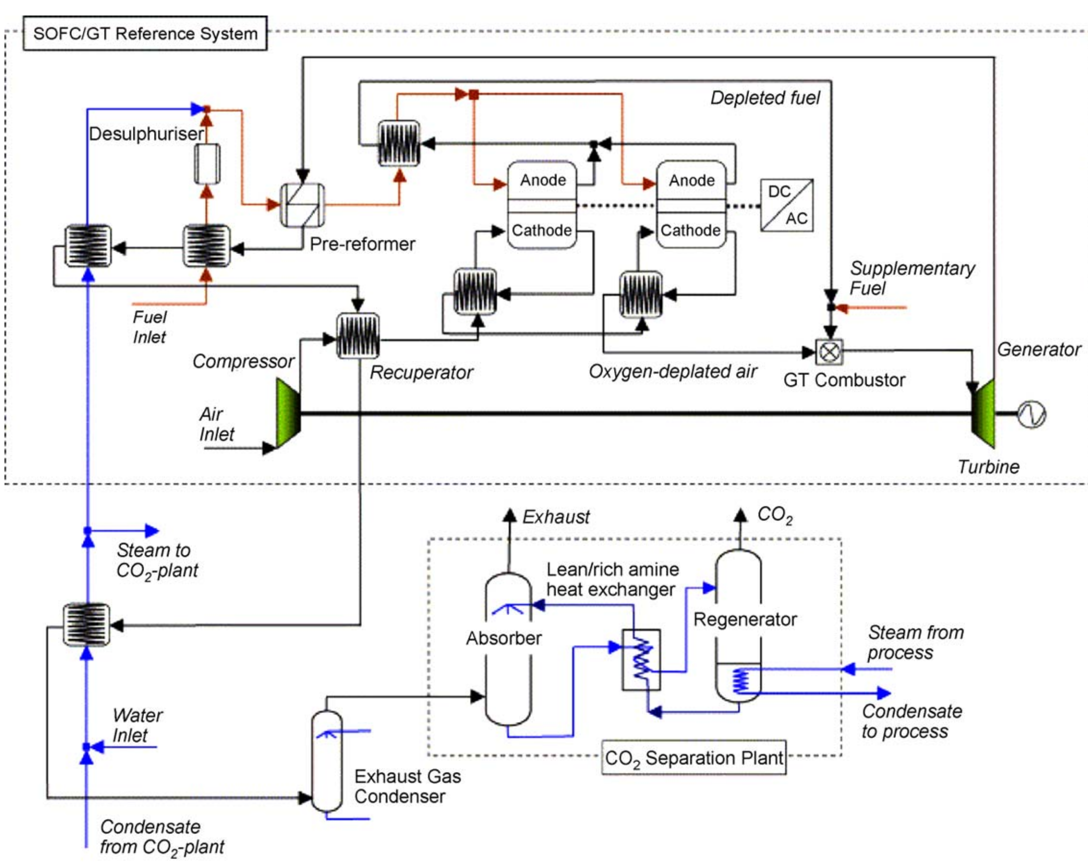


Fig. 8. System layout for the SOFC–GT with CO_2 capture [36].

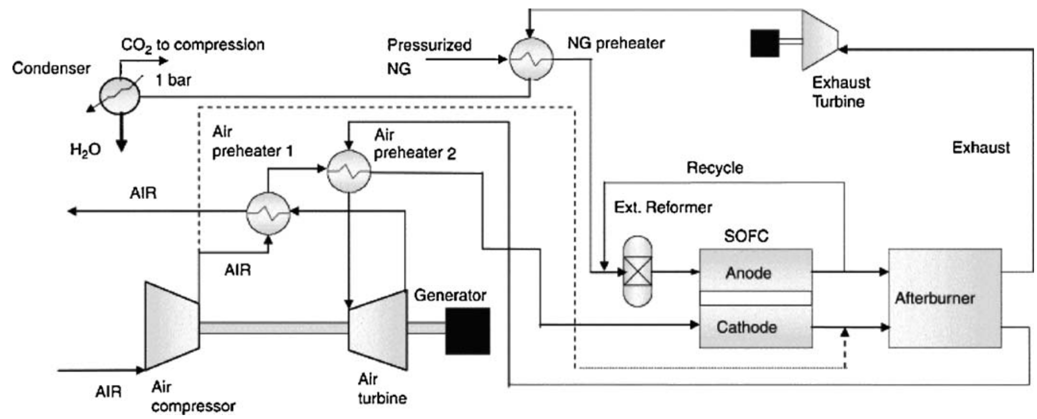


Fig. 9. Simplified PFD of the SOFC–GT concept [56].

results, they claimed that the SOFC–GT–CO_2 capture system could be the most attractive alternative for NG-based DG in terms of efficiency and CO_2 emission reduction.

In 2006, Kvamsdal et al. presented a paper [56] to support that this system could be the most competitive among the various MW-scale, NG-based power plant options. Their system included a 400 MW SOFC–GT with a condenser as a CO_2 capture unit and the configuration is shown in Fig. 9.

In this paper, they claimed a system efficiency of 67.3%, which was the highest value among the nine different conceptual systems they examined. Furthermore, they also claimed that the CO_2 capture efficiency of their system was even higher than that of the other reference systems equipped with the chemical looping combustion, auto-thermal reforming or amine absorption.

In 2007, Franzoni et al. [14] also addressed the important results of this system. They compared the performances of the three SOFC hybrid systems listed in Table 4: without CO_2 capture, with an amine absorption CO_2 capture unit and with a condensation CO_2 capture unit. In this simulation work, they claimed that the system with the condensation CO_2 capture was the most attractive in terms of efficiency, CO_2 capture and costs.

Considering the efforts described above and the other works [57–60] listed in Table 4, the average electricity and capture efficiencies of this system based on NG fuel were estimated to be about 60 and 86.6%, respectively. Therefore, this system is the best among the FC hybrid systems in terms of CO_2 emission reduction. These results might be critical data for addressing the contribution of FC systems to CO_2 emission reduction in the DG system. In other words, when this system is used for NG-based DG application instead of the traditional burning system, the electricity efficiency will be doubled and the CO_2 emission will be decreased to 13.4% of the traditional CO_2 emission.

5. Prerequisites and the future

Before describing the contribution of the FC system to CO_2 emission reduction, various intensive discussions on the technology and development of the system are required. There are two key points. Firstly, the completion and stabilization of the FC technology in order to lower its cost and preserve its high efficiency with a long operating life, and secondly, the CCS technologies. The CCS technology has not been entirely applied to the contribution of the FC to CO_2 emission reduction. It is critical to every CO_2 emission process. According to the IPCC reports [61], CCS is the most promising technology to mitigate CO_2 emissions. The reports also estimated that current global emissions will be reduced by 15–55% during the 21st century by deploying CCS technology. However, many researchers expect that it will take about 20 years for CCS to be practically used, which matches the period required for full commercialization of the FC system. Therefore, CO_2 emission reduction by the application of FC systems in the transportation and stationary fields will be achieved within 20 years.

6. Conclusions

It is clear that the FC and its hybrid system can substantially reduce CO_2 emissions. In the present paper, the CO_2 emission reductions achieved by using the FC or its hybrid system in three application fields was estimated based on some assumptions and some previously published results. The conclusions are as follows:

- *In the mobile application field*: When the DMFC system is used as the power supply in portable or mobile application fields, the amount of CO_2 emission from the DMFC use was estimated to be almost the same as the CO_2 avoided by using it. Furthermore, the amount of CO_2 released in this field was negligible compared to the total GHG emission. Therefore, the application of the FC system in this field will have little or no influence on CO_2 emission reduction.
- *In the transportation application fields*: The benefit of FC in this field is directly dependant on H_2 production. In the mid-term, the pre-combustion technology (with carbon capture) remains the most feasible technology to produce H_2 in terms of CO_2 emission reduction. If the FCV system uses the H_2 produced by this process, the CO_2 emission in this field could be decreased to 70–80% of the traditional CO_2 emission from the gasoline- or diesel-based ICE vehicle systems.
- *In the stationary* (*DG*) *application fields*: To reduce the CO_2 emissions in the stationary application field, FC can be most effectively operated as DG. The four possible system types are the MCFC hybrid, SOFC hybrid and each system integrated with a CO_2 capture unit. Among them, the SOFC hybrid system with a CO_2 capture unit was considered the best as it doubled the electricity efficiency compared to the traditional combustion cycle and decreased the CO_2 emission level to 13.4% of the traditional CO_2 emission.

However, the FC and CCS technologies need to be fully developed before the FC can make a complete contribution to CO_2 emission reduction.

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